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# Bearing Strength of Untightened Double-Shear Bolted Connections in Cold-Formed Steel Construction

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# Bearing Strength of Untightened Double-Shear Bolted Connections in Cold-Formed Steel Construction

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## Abstract

This paper presents the experimental investigation of cold-formed steel double-shear bolted connections where both the bolt head and the nut are not in contact with the outer sheets. The inner sheet of each specimen is not constrained from out-of-plane distortion or bulging downstream of the bolt, and fails in bearing. Based on a series of tests involving specimens having bolt diameters ranging from 12 to 16 mm and sheet thicknesses ranging from 1.5 to 3.0 mm, it has been found that the absence of out-of-plane constraint in untightened bolted connections leads to much lower bearing capacities than predicted by the specification's bearing strength equation. The effect is more pronounced for thinner sheets. An interesting finding is that the threaded bolt specimens had higher bearing capacities than the corresponding ones with shank bolts. It appears that the bolt threads provided some out-of-plane constraint to the connected sheet.

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## Introduction

The design equations for the bearing strengths of double-shear bolted connections in the cold-formed steel design specifications (AISI 2016 and SA/SNZ 2005) are based on test results where the critical ply (the inner sheet) was constrained from out-of-plane distortion and bulging by the clamping force of the bolt (Yu & Mosby 1981, Wallace et al. 2001a, b). The clamping force normally results from snug-tightening the bolt, which ensures the bolt head and nut to be in close contact with the outer sheets as illustrated in Figure 1. Such a constraint can significantly increase the apparent bearing strength of the connected ply. Yu & Mosby (1981) indicated that the installation torque can influence the bearing capacity of bolted connections having a large ratio of bolt diameter to sheet thickness. However, in certain applications the critical ply is not constrained from out-of-plane distortion or bulging (Yu & Mark 2013), including truss members and frame braces where the plies are not in (direct or indirect) contact with either the bolt head or the nut, or both. In such cases, the commentary to Section J3 of AISI S100-16 (AISI 2016) requires laboratory tests be conducted to determine the performance of the connections.

The present work investigates the behavior and strength of untightened bolted connections in cold-reduced steel sheets failing in bearing. It explores the implications of applying the bearing strength provisions given in Section J3.3.1 of AISI S100-16 (AISI 2016) to untightened bolted connections. It includes threaded and shank bolts in the experimental program.

The present data comprise the test results of 64 untightened double-shear bolted connections where the critical ply failed in pure bearing. There are a total of 16 configurations involving threaded bolts and another 16 configurations involving shank bolts. The varied parameters are sheet thickness, bolt diameter, material ductility and loading direction. Bolt hole deformation is not considered, and the bearing capacity corresponds to the ultimate test load.

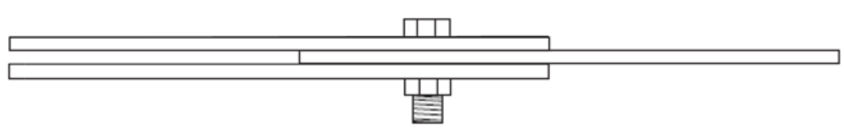


Figure 1 Clamped double-shear bolted connection

**Current design equation**

Section J3.3.1 of AISI S100-16 (AISI 2016) specifies that, when deformation around the bolt hole is not a design consideration, the nominal bearing strength $P_{nb}$ of the connected sheet for each loaded bolt shall be determined as

$$P_{nb} = C\ m_f\ d\ t\ F_u \tag{1}$$

where $C$ is the bearing factor, which depends on the ratio of the diameter $d$ to the connected sheet thickness $t$, $m_f$ is the modification factor, which accounts for the type of bearing connections, and $F_u$ is the material tensile strength.

The bearing factor $C$ is given in Table J3.3.1-1 of AISI S100-16 (AISI 2016), reproduced as Table 1 for connections with standard holes. The table is based on the recommendations of Wallace et al. (2001b).

Table 1: Bearing factor $C$ for bolted connections with standard holes (AISI 2016)

| ***d/t*** | ***C*** |
|---|---|
| $d/t < 10$ | 3.0 |
| $10 \leq d/t \leq 22$ | $4 - 0.1\ (d/t)$ |
| $d/t > 22$ | 1.8 |

The values of $m_f$ vary from 0.55 for certain single-shear connections or outside sheets of double-shear connections without washers to 1.33 for the inside sheet of a double-shear connection using standard holes, which is the case in the present work.

**Test materials**

The G2 and G450 cold-reduced steel sheets used in present experimental tests have the trade names GALVABOND® and GALVASPAN® respectively. These materials were manufactured and supplied by BlueScope Steel Port Kembla Steelworks, Australia. The average yield stresses $F_y$, tensile strengths $F_u$ and elongations at fracture over different gauge length are provided in Tables 2 and 3. The variables $\varepsilon_{15}$, $\varepsilon_{25}$, $\varepsilon_{50}$ are elongations at fracture over 15mm, 25mm, 50mm, respectively, and $\varepsilon_{uo}$ is the uniform elongations outside the fracture. The suffix "R" denotes the loading to be in the rolling direction, and the suffix "T" denotes loading in the direction perpendicular to the rolling direction.

Table 2: Average material properties for G2 sheet steels (Teh & Uz 2014)

| **Designation** | $F_y$ **(MPa)** | $F_u$ **(MPa)** | $F_u / F_y$ | $\varepsilon_{15}$ **(%)** | $\varepsilon_{25}$ **(%)** | $\varepsilon_{50}$ **(%)** | $\varepsilon_{uo}$ **(%)** |
|---|---|---|---|---|---|---|---|
| 1.5 mm T | 390 | 430 | 1.10 | 58.1 | 47.8 | 32.2 | 17.3 |
| 1.5 mm R | 320 | 400 | 1.25 | 55.2 | 45.9 | 37.7 | 24.5 |
| 2.4 mm T | 345 | 395 | 1.14 | 68.5 | 53.8 | 40.4 | 24.1 |
| 2.4 mm R | 310 | 390 | 1.26 | 62.4 | 51.5 | 40.1 | 26.8 |

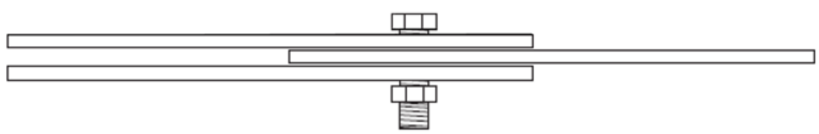
Table 3: Average material properties for G450 sheet steels (Teh & Uz 2014)

| **Designation** | $F_y$ **(MPa)** | $F_u$ **(MPa)** | $F_u / F_y$ | $\varepsilon_{15}$ **(%)** | $\varepsilon_{25}$ **(%)** | $\varepsilon_{50}$ **(%)** | $\varepsilon_{uo}$ **(%)** |
|---|---|---|---|---|---|---|---|
| 1.5 mm T | 610 | 630 | 1.03 | 15.5 | 10.5 | 8.1 | 4.5 |
| 1.5 mm R | 555 | 590 | 1.06 | 21.5 | 16.3 | 12.0 | 6.9 |
| 3.0 mm T | 570 | 610 | 1.07 | 27.5 | 18.0 | 10.9 | 6.3 |
| 3.0 mm R | 520 | 555 | 1.07 | 30.5 | 21.4 | 14.8 | 8.2 |

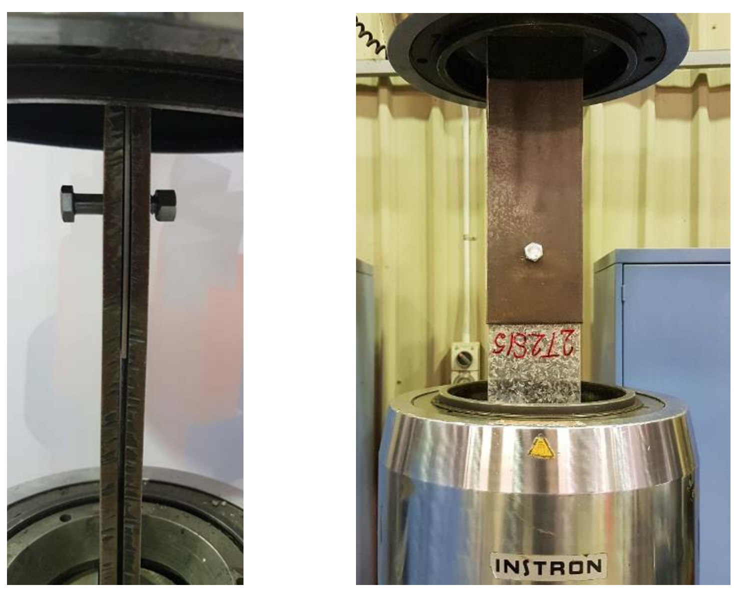
As can be seen from Tables 2 through 3, the G2 steel is much more ductile than the G450 steel. G2 is classified as a formability grade, while G450 is a structural grade (SA 2011).

**Specimen configurations and test set-up**

All tested specimens were single bolted double-shear connections, where the bolt head and nut were not in contact with the outer sheets, as shown in Figure 2. The concentrically loaded inner sheet was the critical element since the two outer sheets were 9 mm thick steel plates having a measured yield stress of 550 MPa. Each of the inner sheets was 100 mm wide, and the distance between each bolt and the downstream end was 75 mm to ensure that bearing failure was the governing mode. Since there were some gaps between the bolt head and nut and the outer sheets, the inner sheet was not constrained from out-of-plane distortion or bulging downstream of the bolt as it failed in bearing.



(a)




(b)

Figure 2 Present set-up: (a) Schematic; (b) As tested

The varied parameters in the present experimental program are:

- Grade and thickness of the inner sheet: 1.5 mm and 2.4 mm G2 sheets, 1.5 mm and 3.0 mm G450 sheets.
- Bolt type: threaded and shank.
- Bolt diameter: 12 mm (M12) and 16 mm (M16) diameter bolts are used for each type of bolt.
- Loading direction: Some specimens were loaded in the rolling direction of the cold-reduced steel sheet, others in the direction perpendicular to the rolling direction.

The bolt hole of each specimen was drilled 1 mm larger than the bolt diameter. The specimens were loaded at a stroke rate of 2 mm per minute.

**Test results and discussions**

The ratios of the ultimate test load $P_{test}$ to the estimates $P_{nb}$ obtained using Equation (1), called the professional factors, of specimens with threaded bolts and with shank bolts are provided in Tables 4 and 5, respectively. The ultimate test loads are the average values of two specimens for each configuration. Tables 4 and 5 also list the nominal thicknesses, the nominal bolt diameter to thickness ratios, the loading directions and the (measured) material tensile strengths. An empty cell in the tables represents the same value as the data in the above cell.

The test results shown in Tables 4 and 5 indicate that the untightened bolt condition has a significant effect on the bearing capacity of a bolted connection in cold-reduced sheet steel. All the professional factors are well below the value of unity. Figure 3 shows the differences in the exact failure mode between a hand-tightened specimen and an untightened specimen, the latter tested in the present experimental program. The hand-tightened specimen in Figure 3(a) was tested in a separate program, and had an ultimate test load that was more than double that of the untightened specimen in Figure 3(b). The hand-tightened specimen was constrained by the outer sheets from distorting out-of-plane, while the untightened one underwent notable out-of-plane distortion downstream of the bolt.

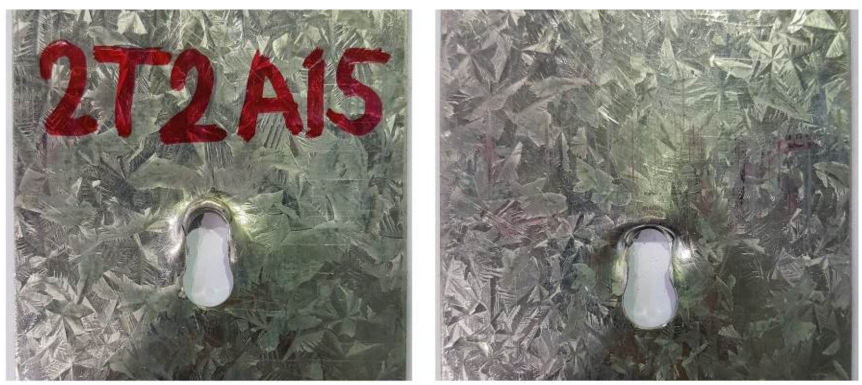
Table 4: Test results for thread bolted specimens

| Config. | Grade | $t$ (mm) | $d/t$ | Direction | $F_u$ (MPa) | $P_{test}/P_{nb}$ |
|---|---|---|---|---|---|---|
| 2R2A15 | G2 | 1.5 | 8.00 | R | 400 | 0.58 |
| 2R6A15 | | | 10.67 | | | 0.55 |
| 2T2A15 | | | 8.00 | T | 430 | 0.49 |
| 2T6A15 | | | 10.67 | | | 0.66 |
| 4R2A15 | G450 | | 8.00 | R | 590 | 0.51 |
| 4R6A15 | | | 10.67 | | | 0.53 |
| 4T2A15 | | | 8.00 | T | 630 | 0.44 |
| 4T6A15 | | | 10.67 | | | 0.45 |
| 2R2A24 | G2 | 2.4 | 5.00 | R | 390 | 0.81 |
| 2R6A24 | | | 6.67 | | | 0.81 |
| 2T2A24 | | | 5.00 | T | 395 | 0.82 |
| 2T6A24 | | | 6.67 | | | 0.68 |
| 4R2A30 | G450 | 3.0 | 4.00 | R | 555 | 0.85 |
| 4R6A30 | | | 5.33 | | | 0.79 |
| 4T2A30 | | | 4.00 | T | 610 | 0.70 |
| 4T6A30 | | | 5.33 | | | 0.70 |

Table 5: Test results for shank bolted specimens

| Config. | Grade | $t$ (mm) | $d/t$ | Direction | $F_u$ (MPa) | $P_{test}/P_{nb}$ |
|---|---|---|---|---|---|---|
| 2R2S15 | G2 | 1.5 | 8.00 | R | 400 | 0.55 |
| 2R6S15 | | | 10.67 | | | 0.46 |
| 2T2S15 | | | 8.00 | T | 430 | 0.53 |
| 2T6S15 | | | 10.67 | | | 0.61 |
| 4R2S15 | G450 | | 8.00 | R | 590 | 0.49 |
| 4R6S15 | | | 10.67 | | | 0.46 |
| 4T2S15 | | | 8.00 | T | 630 | 0.44 |
| 4T6S15 | | | 10.67 | | | 0.38 |
| 2R2S24 | G2 | 2.4 | 5.00 | R | 390 | 0.86 |
| 2R6S24 | | | 6.67 | | | 0.69 |
| 2T2S24 | | | 5.00 | T | 395 | 0.73 |
| 2T6S24 | | | 6.67 | | | 0.65 |
| 4R2S30 | G450 | 3.0 | 4.00 | R | 555 | 0.72 |
| 4R6S30 | | | 5.33 | | | 0.66 |
| 4T2S30 | | | 4.00 | T | 610 | 0.67 |
| 4T6S30 | | | 5.33 | | | 0.62 |


(a)




(b)

Figure 3 Effect of clamping on the exact failure mode: (a) hand-tightened specimen; (b) untightened specimen

The adverse effect of out-of-plane distortion was less severe for thicker specimens such as Specimen 4R6A30 shown in Figure 4(b), as evidenced from the professional factors given in Tables 4 and 5. It can be seen from Figure 4 that the (unsymmetrical) out-of-plane distortion was more pronounced in the 1.5 mm specimen than in the 3.0 mm specimen.


(a)


(b)

Figure 4 Effect of sheet thickness on out-of-plane distortion: (a) 1.5 mm specimen; (b) 3.0 mm specimen

The effect of sheet thickness on the extent of out-of-plane distortion or bulging has been more or less taken into account in the specification through the use of Table 1, where the bearing factor $C$ tends to decrease with increasing ratios of the bolt diameter $d$ to the sheet thickness $t$. However, it is clear from Tables 4 and 5 that the bearing coefficients in Table 1 do not sufficiently account for the untightened bolt condition tested in the present work.

The effects of material ductility and rolling directions found in the present work is consistent with those of Teh & Uz (2014) for hand-tightened connections. It can be seen from Tables 4 and 5 that, for the same nominal geometries, the professional factors of the more ductile G2 sheet steel specimens are generally higher than those of the G450 sheet steel specimens. Furthermore, in most cases the specimens loaded in the rolling direction had relatively higher professional factors than comparable ones loaded perpendicular to the rolling directions, even though the material tensile strength is lower in the rolling direction.

It can also be seen from Tables 4 and 5 that, for the same nominal geometries, the professional factors of the shank bolt specimens are generally lower than the thread bolted specimens. This unintuitive outcome was probably due to the beneficial out-of-plane constraining effect of bolt threads in cold-reduced steel sheets where the bolts were untightened. Figure 5 shows the difference in bearing deformations between the thread bolted and the shank bolted specimens, each composed of 3.0-mm G450 sheet steel and having a 16-mm bolt.


(a)


(b)

Figure 5 Effect of bolt threads: (a) thread specimen; (b) shank specimen

## Conclusion

Experimental tests have been conducted on untightened double-shear bolted connections composed of G2 and G450 sheet steels in order to investigate the effects of not having any out-of-plane constraint against the bearing deformations (out-of-plane distortion and/or bulging) downstream of the bolt. In each of the tested specimens, the inside sheet failed in bearing. The investigation included threaded and shank bolts. The varied parameters are sheet thickness, bolt diameter, material ductility and loading direction.

The experimental results show that all the untightened bolted connections had ultimate bearing capacities significantly lower than the estimates given by the specification's bearing strength equation. In some cases, the ultimate test load was less than half of the specification's estimate.

The absence of out-of-plane constraint had a more pronounced effect on the thinner specimens, which experienced substantial out-of-plane distortion downstream of the bolt.

It has been confirmed that the more ductile the steel material is, the higher the professional factor for the bearing capacity. Also, the specimens loaded in the rolling direction of the steel sheet had higher professional factors when computed, based on the material tensile strength in the same direction.

An interesting finding is that, for untightened double-shear connections, the threaded bolt specimens had higher bearing capacities than the corresponding ones with shank bolts. It appears that the bolt threads provided some out-of-plane constraint to the connected sheet.

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**References**

AISI (2016) *North American Specification for the Design of Cold-Formed Steel Structural Members 2016 Edition*, American Iron and Steel Institute, Washington, DC.

Rogers, C. A., and Hancock, G. J. (1998) "Bolted connection tests of thin G550 and G300 sheet steels," *Journal of Structural Engineering*, 124 (7), 798-808.

SA (2011) Continuous hot-dip metallic coated steel sheet and strip—Coatings of zinc and zinc alloyed with aluminium and magnesium, AS 1397-2011, Standards Australia, Sydney.

SA/SNZ (2005) *Cold-Formed Steel Structures*, AS/NZS 4600:2005, Standards Australia/Standards New Zealand, Sydney, Australia.

Teh, L. H., and Uz, M. E. (2014) "Effect of loading direction on the bearing capacity of cold-reduced steel sheets," *Journal of Structural Engineering*, 140 (12), 06014005.

Wallace, J. A., Schuster, R. M., and LaBoube, R. (2001a) *Testing of Bolted Cold-formed Steel Connections in Bearing (With and Without Washers)*, Research Report RP01-4, Committee on Specifications for the Design of Cold-formed Steel Structural Members, American Iron and Steel Institute, Washington, DC.

Wallace, J. A., Schuster, R. M., and LaBoube, R. (2001b) *Calibrations of Bolted Cold-formed Steel Connections in Bearing (With and Without Washers)*, Research Report RP01-5, Committee on Specifications for the Design of Cold-formed Steel Structural Members, American Iron and Steel Institute, Washington, DC.

Yu, C., and Mark, X. P. (2013) "Bearing strength of cold-formed steel bolted connections with a gap," *Thin-Walled Structures*, 67, 110–115.

Yu, C., and Xu, K. (2010) *Cold-Formed Steel Bolted Connections Using Washers on Oversized and Slotted Holes – Phase 2*, Research Report RP10-2, Committee on Specifications for the Design of Cold-formed Steel Structural Members, American Iron and Steel Institute, Washington, DC.

Yu, W. W., and Mosby, R. L. (1981) *Bolted Connections in Cold-formed Steel Structures*, Final Report, Civil Engineering Study 81-1, University of Missouri-Rolla, Rolla, MO.